MECHANICAL DESIGN AND MANUFACTURING OF COSθ-TYPE MAGNETS

Arnaud Devred
CEA/Saclay

Technology School on Superconducting Magnets
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Contents

- Support Against Lorentz Force
- Azimuthal Pre-Compression
- Radial Support
- End Support
- Manufacturing of NbTi Magnets

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- **Support Against Lorentz Force**
- Azimuthal Pre-Compression
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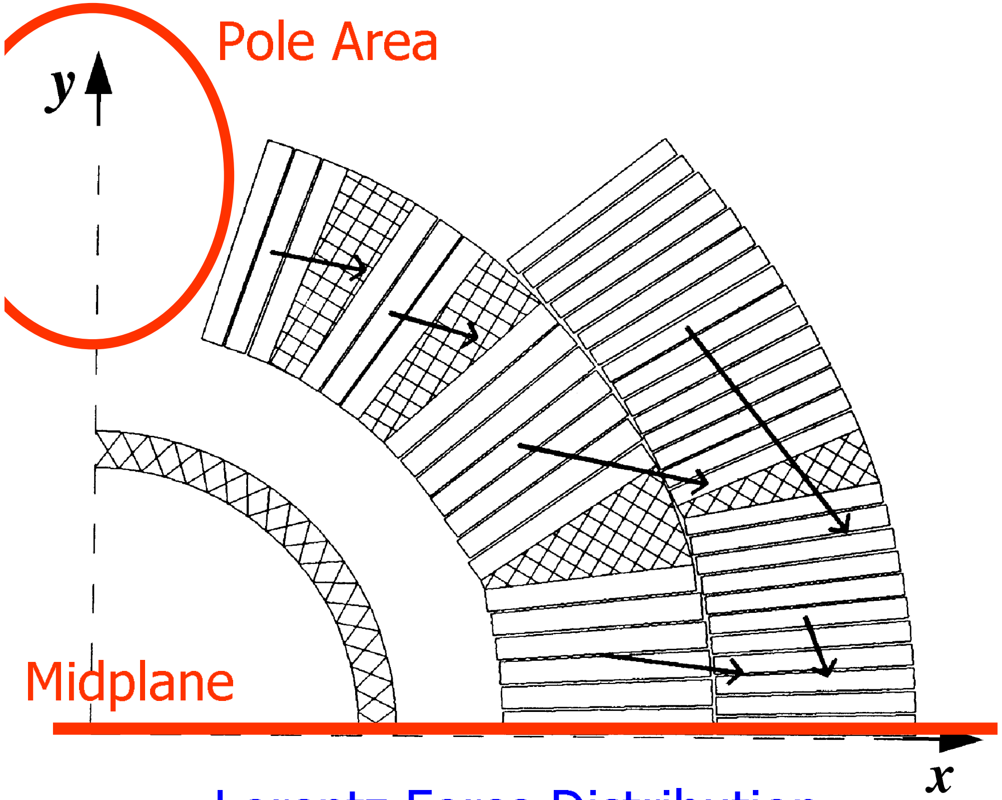
Lorentz Force Components (1/3)

- In a cosθ-type coil, the Lorentz force has three main components
  - an azimuthal component,
  - a radial component,
  - an axial component.

Lorentz Force Components (2/3)

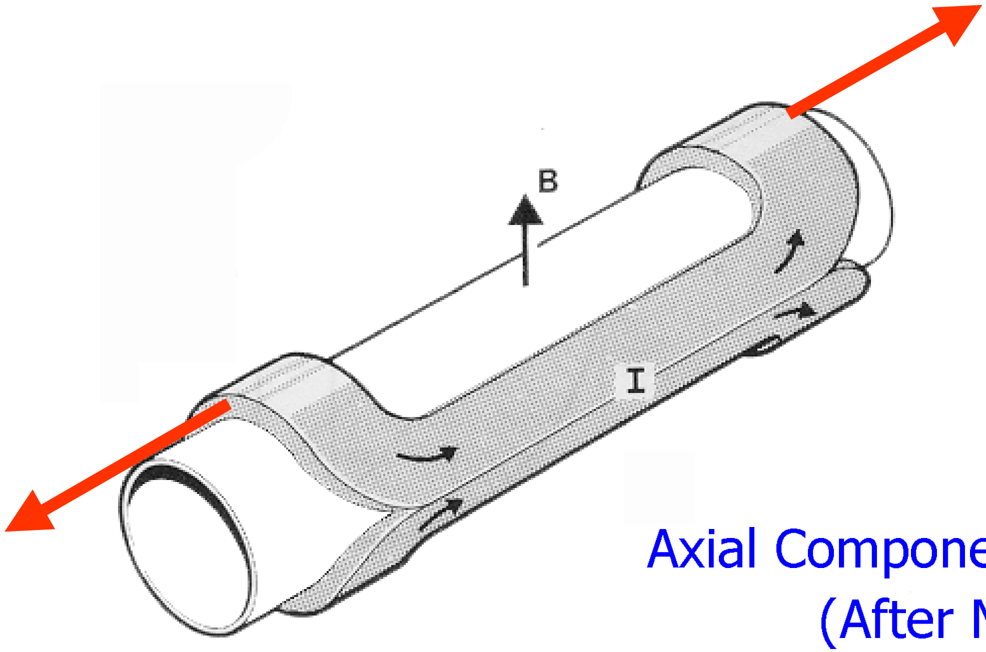


Lorentz Force Distribution
in 2-D X-section
of SSC Arc Dipole Magnet Coil
(Courtesy R. Gupta)

- The azimuthal component tends to squeeze the coil towards the midplane.
- The radial component tends to bend the coil outwardly, with a maximum displacement at the coil assembly midplane.

Lorentz Force Components (3/3)

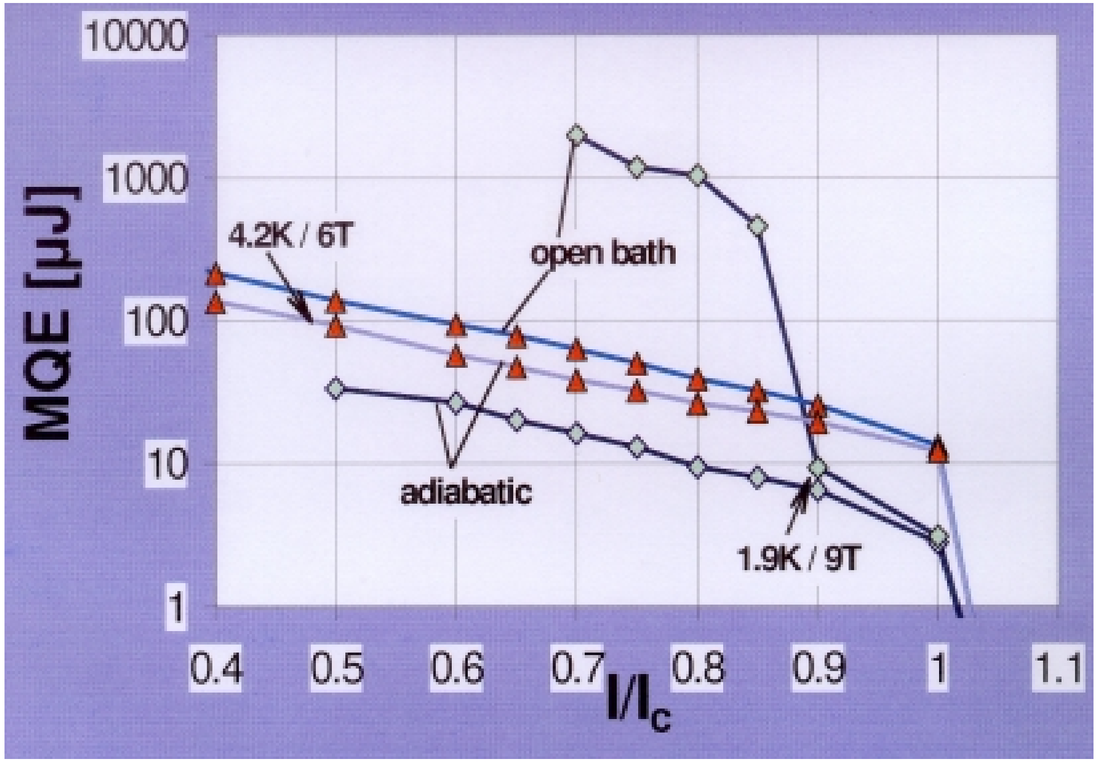
- The axial component, which arise from the solenoidal field generated by the conductors' turnaround in the coil ends, tends to stretch the coil outwardly.



Axial Component of Lorentz Force
(After M.N. Wilson)

Stability Against Mechanical Disturbances (1/4)

- Accelerator magnets are operated very close to the critical current limit of their cables *(see lecture on magnetic design).*



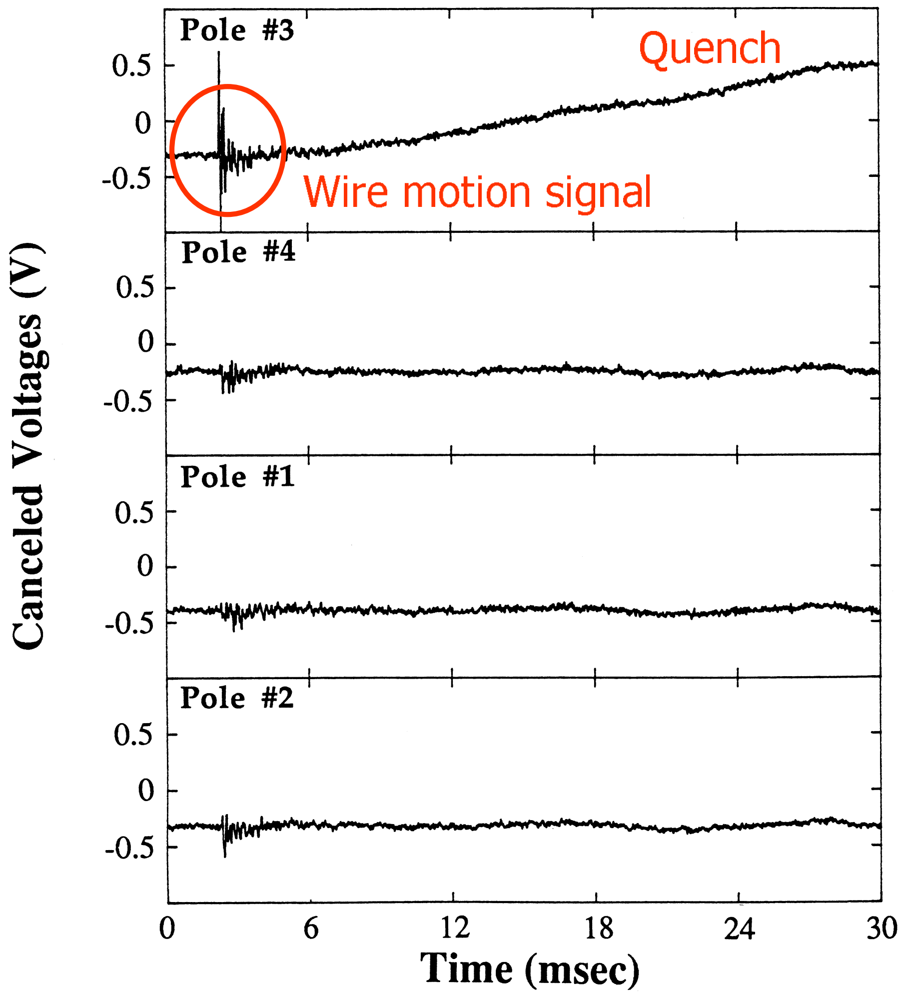
- As a result, the minimum energy deposition needed to trigger a quench, referred to as Minimum Quench Energy (MQE), is very small.

MQE Measurements on LHC-Type Wire (Courtesy P. Bauer)

Stability Against Mechanical Disturbances (2/4)

- In particular, the MQE is of same order of magnitude as the electromagnetic work produced by minute wire motions in the magnet coil.
- If these motions are purely elastic, no heat is dissipated and the coil remains superconducting.

Stability Against Mechanical Disturbances (3/4)



- However, if the motions are frictional, the associated heat dissipation may be sufficient to initiate a quench.

Example of wire motion signal observed in the voltage across a pole of a superconducting quadrupole magnet at KEK (Courtesy K. Tsuchiya)

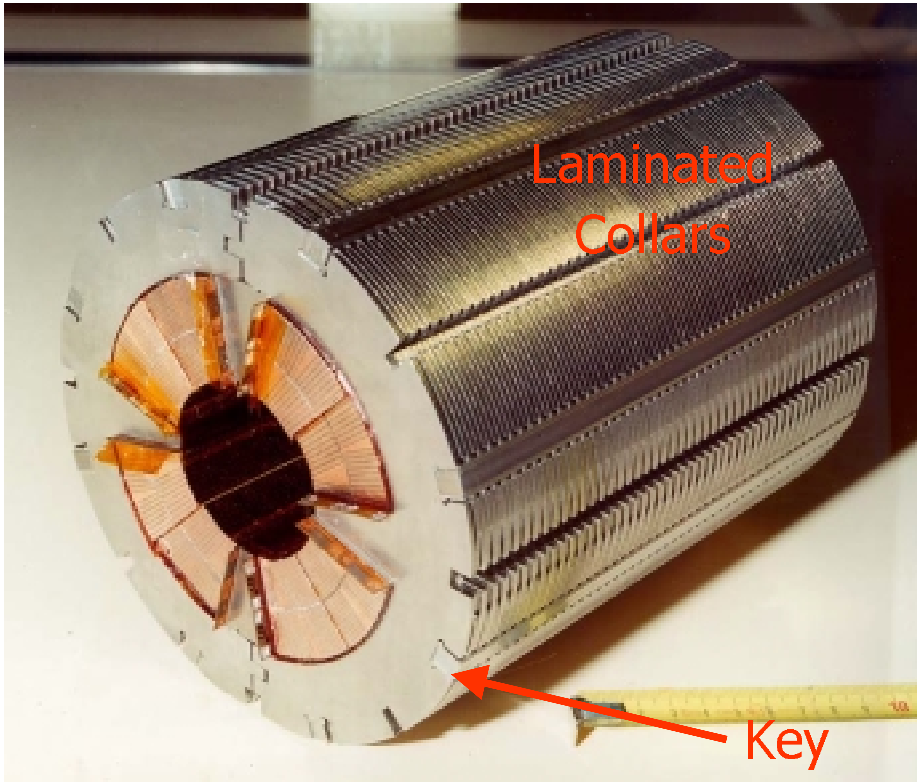
Stability Against Mechanical Disturbances (4/4)

- This leaves only two possibilities
  - to prevent wire or coil motion by providing a rigid support against the various components of Lorentz force,
  - to reduce to a minimum the friction coefficients between potentially moving parts of magnet assembly.

Conceptual Design (1/4)

- The mechanical design concepts used in present cosθ-type accelerator magnets are more or less the same and were developed at the time of the Tevatron.

Conceptual Design (2/4)



Collared-Coil Assembly Section
of LHC Arc Quadrupole Magnet
at CEA/Saclay

- In the radial direction: the coils are confined in a rigid cavity, defined by laminated collars locked around the coil by means of keys or tie rods.
- In the azimuthal direction: the collars are assembled so as to pre-compress the coils.

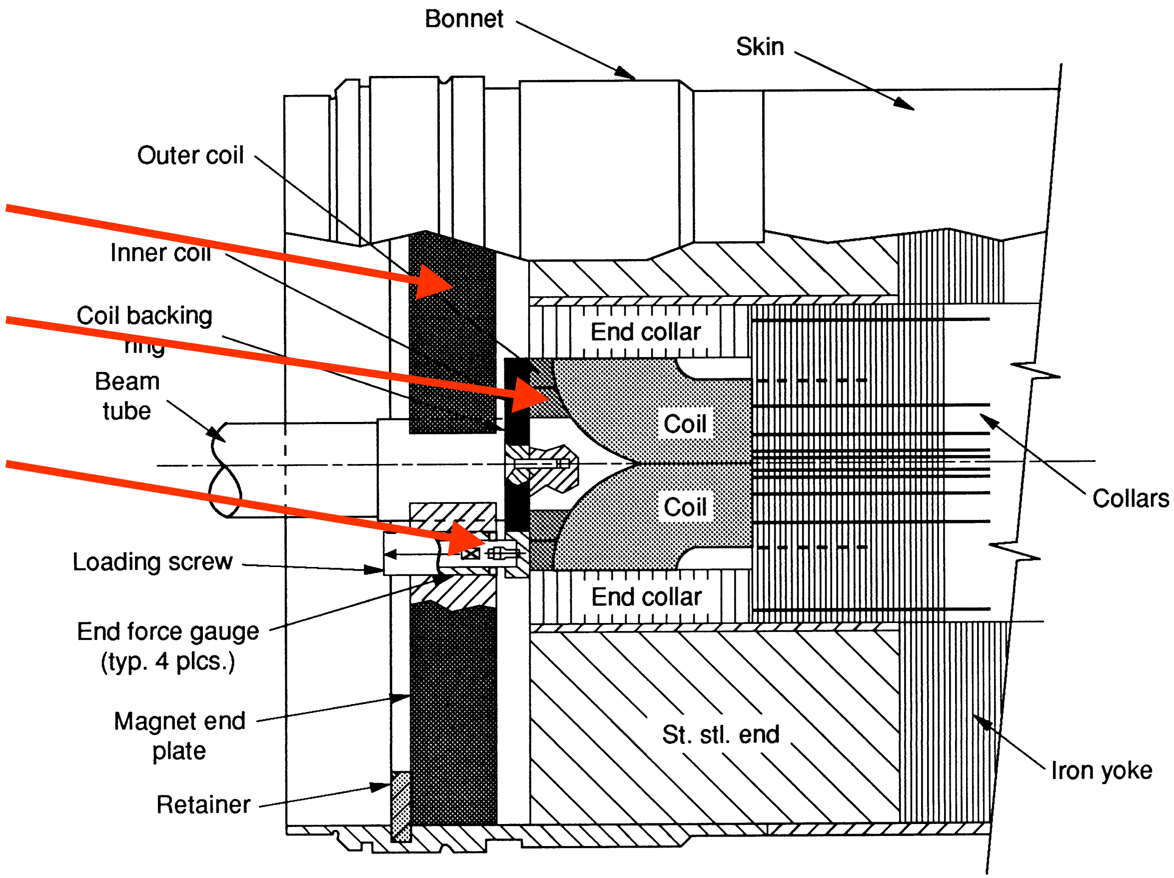
Conceptual Design (3/4)

- In the axial direction: the coils are either free to expand or restrained by means of stiff end plates.

End Plate

Coil End

Loading Screw



SSC Arc Dipole Magnet
End Design
With Stiff End Plate

Conceptual Design (4/4)

- The use of laminated collars, pioneered at the Tevatron, was a real breakthrough in achieving a rigid mechanical support while keeping tight tolerances over magnet assemblies which are a few meters in length and must be mass-produced.
- The laminations are usually stamped by a fine blanking process allowing a dimensional accuracy of the order of 1/100th of a millimeter to be achieved.
- Such accuracy is needed to ensure proper conductor positioning for field quality.

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- Radial Support
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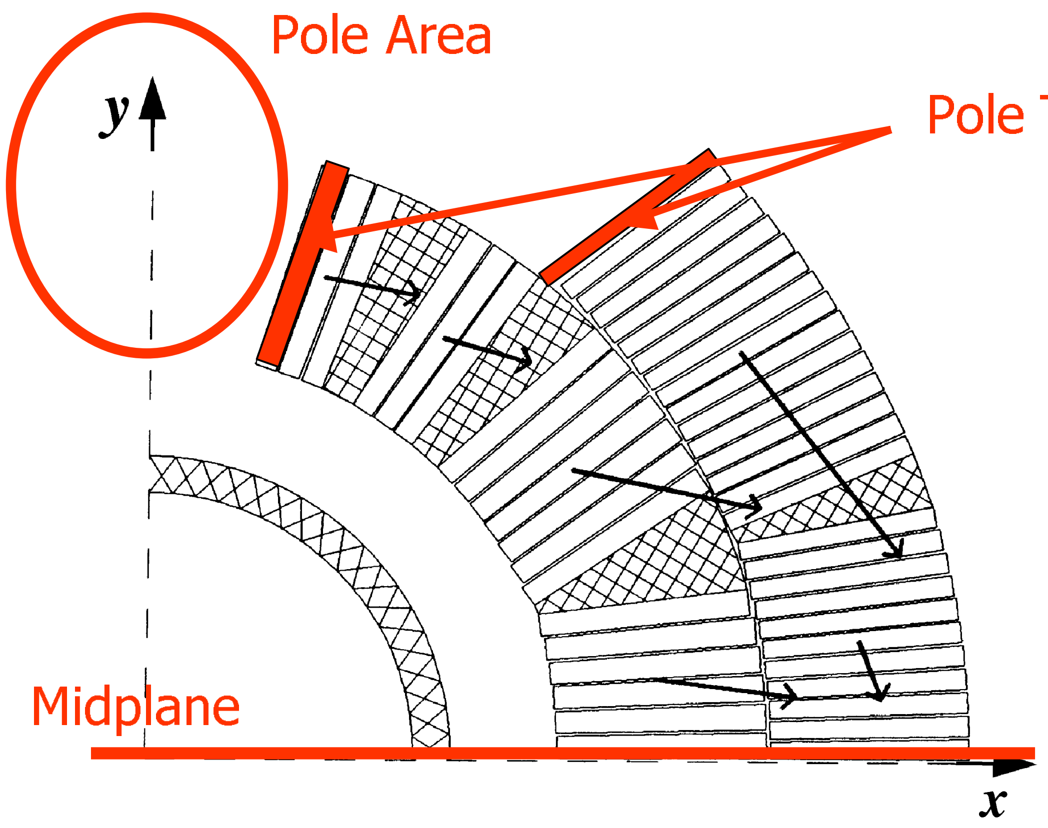
- Manufacturing of NbTi Magnets

Collar Pole Unloading (1/4)

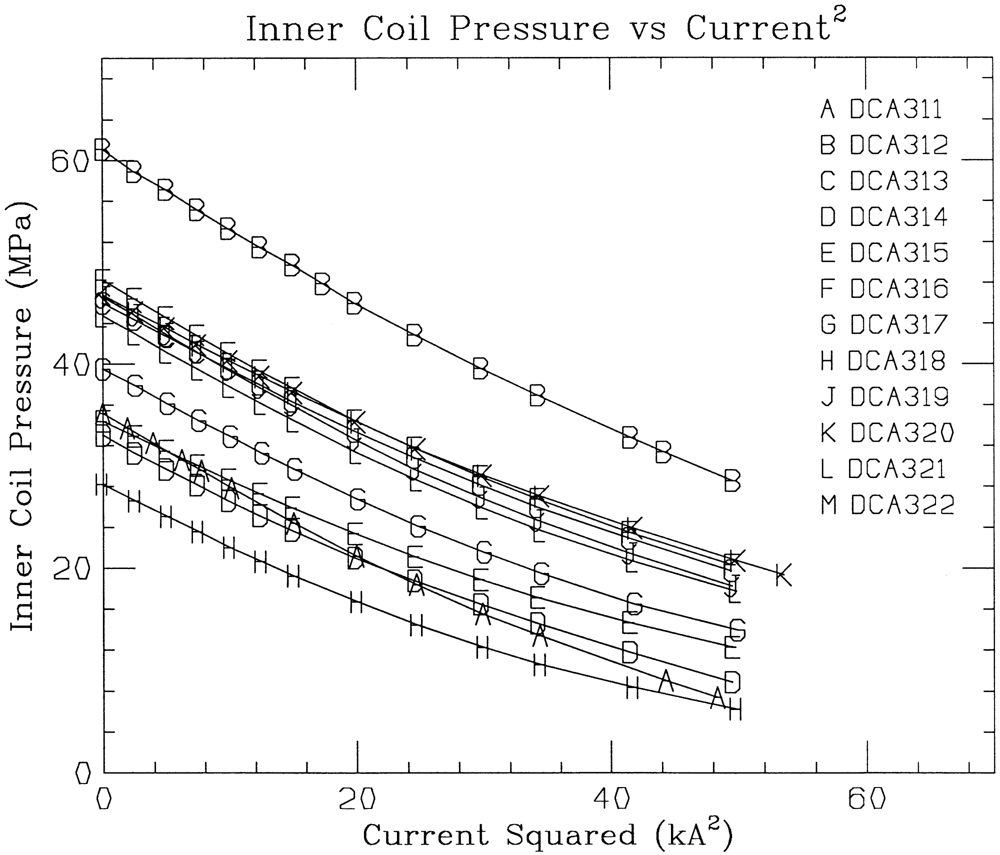
- As we have seen, the azimuthal component of the Lorentz force tends to squeeze the coil towards the midplane.



Lorentz Force Distribution
in 2-D X-section
of SSC Arc Dipole Magnet Coil
(Courtesy R. Gupta)

Collar Pole Unloading (2/4)

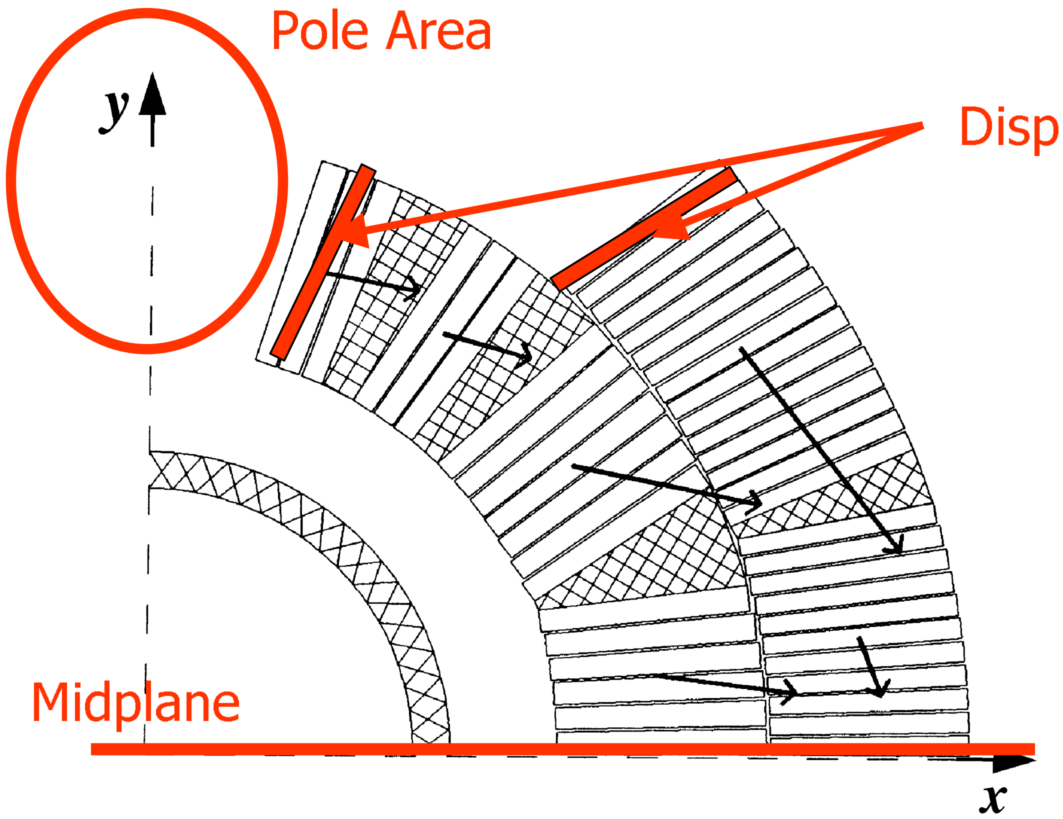
- This results in a progressive unloading of collar pole during excitation.



Collar Pole Unloading Measured on SSC Dipole Magnet Prototypes (Courtesy T. Ogitsu)

Collar Pole Unloading (3/4)

- At high excitation currents (and thus, high fields), it can happen that the coil pole turn moves away from collar pole.



Lorentz Force Distribution
in 2-D X-section
of SSC Arc Dipole Magnet Coil
(Courtesy R. Gupta)

Collar Pole Unloading (4/4)

- Such pole turn displacement distorts central field and creates a risk of mechanical disturbance.
- To prevent full unloading, the collars are assembled and locked around the coils so as to apply an azimuthal pre-compression.
- The pre-compression is applied at room temperature and must be sufficient to ensure that, after cooldown and energization, there is still contact between coil pole turns and collar poles.

Pre-Stress Requirements

- To determine proper level of room temperature pre-compression, at least three effects must be taken into account
  - – stress relaxation and insulation creep following collaring operation,
  - – thermal shrinkage differential between coil and collars during cooldown,
  - – stress redistribution due to azimuthal component of Lorentz force during energization.
- In addition, the collaring operation must be optimized to ensure that the peak pressure seen by the coil does not overstress insulation.

Prestress Loss During Cooldown

- An estimate of the pre-stress loss during cooldown, $\Delta\sigma_{\text{c.d.}}$, is given by

$$\Delta\sigma_{\text{c.d.}} \approx E_{\text{coil}} \, (\alpha_{\text{coil}} - \alpha_{\text{collar}})$$

where E_{coil} is the coil Young's modulus in the azimuthal direction, and α_{coil} and α_{collar} are the thermal shrinkage coefficients of the coils (in the azimuthal direction) and of the collars, integrated between room and liquid helium temperatures.

(Note that the previous equation is derived with the assumption that E_{coil} is constant and the collars are infinitely rigid.)

Thermal Shrinkage Coefficients

- Values of integrated thermal shrinkage coefficients (between 4.2 K and room temperature) for commonly used materials

Titanium	1.5
Low Carbon Steel	2.0
Stainless Steel (304/316)	2.9
Copper (OFHC)	3.1
Aluminum Alloy	4.2
NbTi Cables w. Polyimide Insulation[a)]	~5
Resin-Impregnated Nb_3Sn Cables[a)]	3.5–4

[a)] Depends on cable and insulation parameters.

Collar Material (1/4)

- To limit pre-stress cooldown loss, it is preferable to use for the collars a material whose integrated thermal shrinkage coefficient matches more or less that of the coil.
- From the data shown previously, this suggest the use of aluminum alloy.

Collar Material (2/4)

- However, as described in the next section, it is desirable also that the collars be as rigid as possible and/or have an integrated thermal shrinkage coefficient approaching that of the low-carbon steel used for the yoke.
- This favors austenitic stainless steel, which has a lower integrated coefficient and a higher Young's modulus than aluminum aluminum alloy.

(The Young's modulus of austenitic stainless steel is ~200 Gpa, while that of aluminum alloy is ~75 Gpa.)

Collar Material (3/4)

- Let us note also that austenetic steel has a better resistance to stress cycling at low temperature, but has a higher density (7800 kg/m^3 compared to 2800 kg/m^3 for aluminum) and, thus, is more expensive.

Collar Material (4/4)

- There is no ideal choice between stainless steel and aluminum alloy, and magnets with both types of collar material have been built: HERA dipole magnets and early LHC dipole magnet prototypes use aluminum alloy collars, whereas Tevatron, most SSC dipole magnet prototypes and present LHC dipole magnets use stainless steel collars.
- In any case, whichever collar material material is chosen, it is required to perform a thorough mechanical analysis of the structure under the various loading conditions encountered during assembly and operation.
- This analysis can be validated by performing collaring tests on short coil sections.

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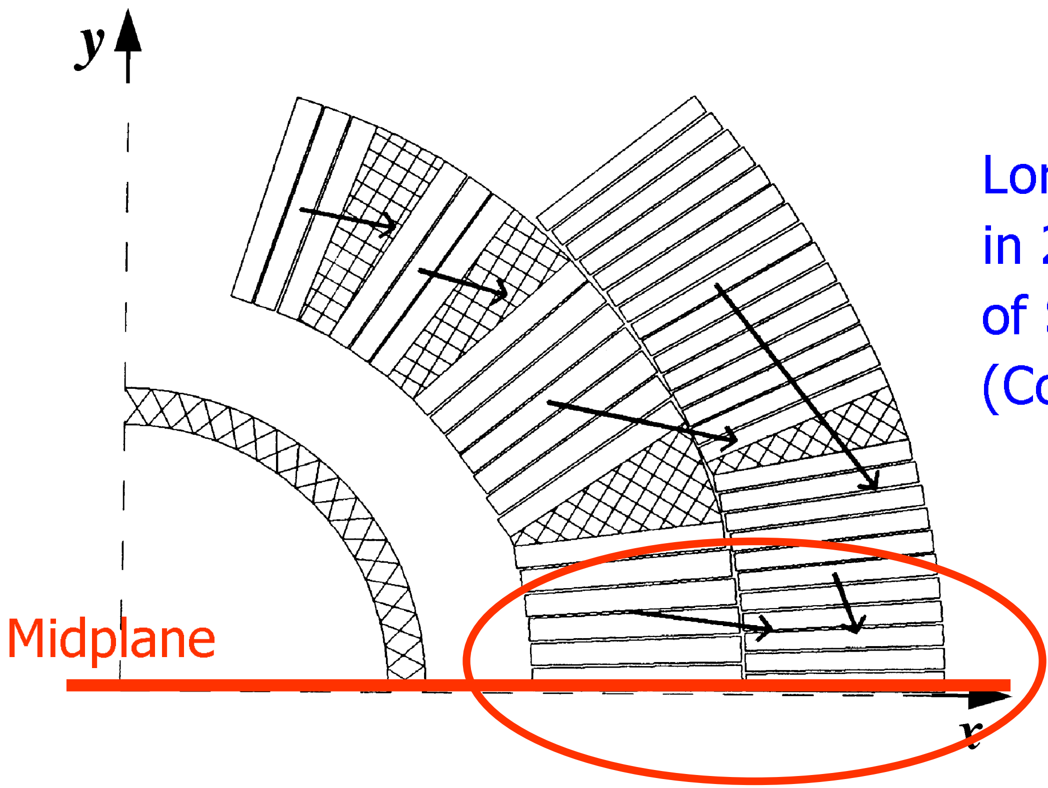
Radial Deflections (1/2)

- As we have seen, the radial component of the Lorentz force tends to bend the coil outwardly, with a maximum displacement at the coil assembly midplane.



Lorentz Force Distribution in 2-D X-section of SSC Arc Dipole Magnet Coil (Courtesy R. Gupta)

Radial Deflections (2/2)

- At high excitation currents (and thus, high fields), this bending can result in shear stresses between coil turns and in an ovalization of the coil assembly (along the horizontal *x*-axis for a dipole magnet coil), which generate field distortions.
- To prevent unwanted displacements and deformations, the radial deflections of the coil assembly are usually limited to, typically, less than 0.05 mm.

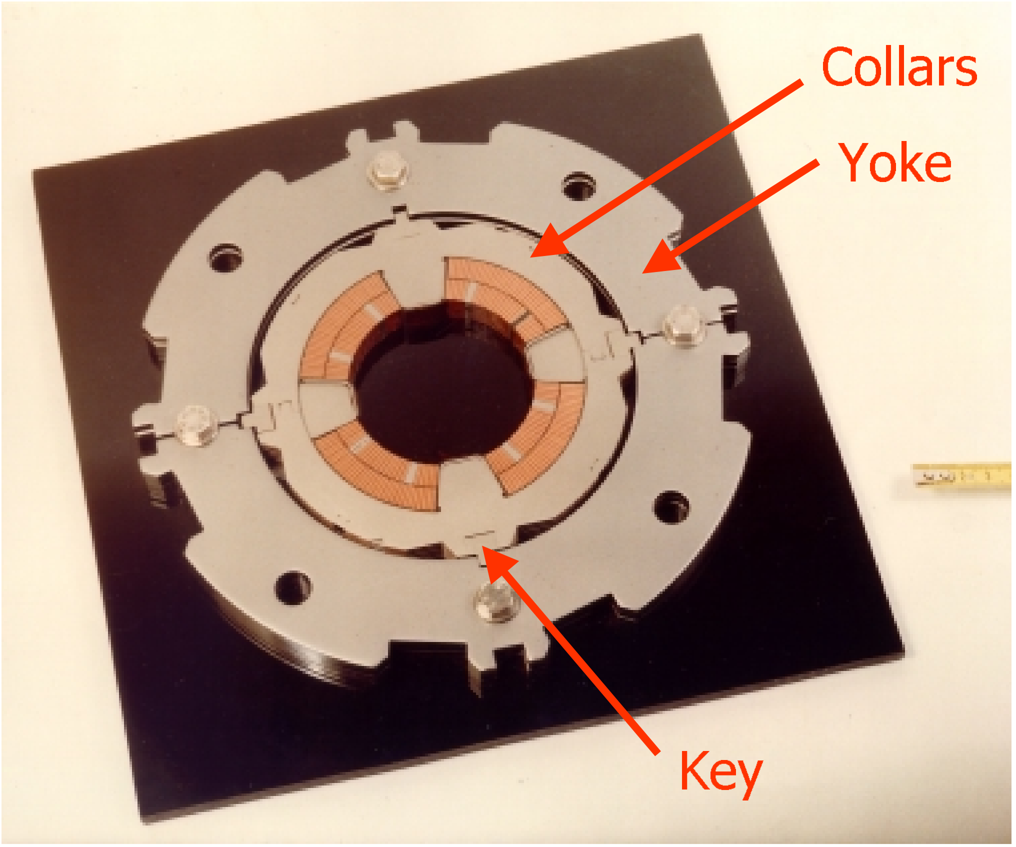
Self-Supported Collared Coils

• The main support against the radial component of the Lorentz force is provided by the collars.

• If the collars can be made wide enough to limit collared-coil assembly deflections within the desired range, there is no need to seek yoke support and the mechanical structure remains fairly simple.

Examples: HERA and LHC arc quadrupole magnet designs developed at CEA/Saclay.

Example: HERA Quadrupole Magnets



- The collared-coil assembly of the HERA arc quadrupole magnet is self-supported and is centered within the iron yoke by means of collar-locking keys.

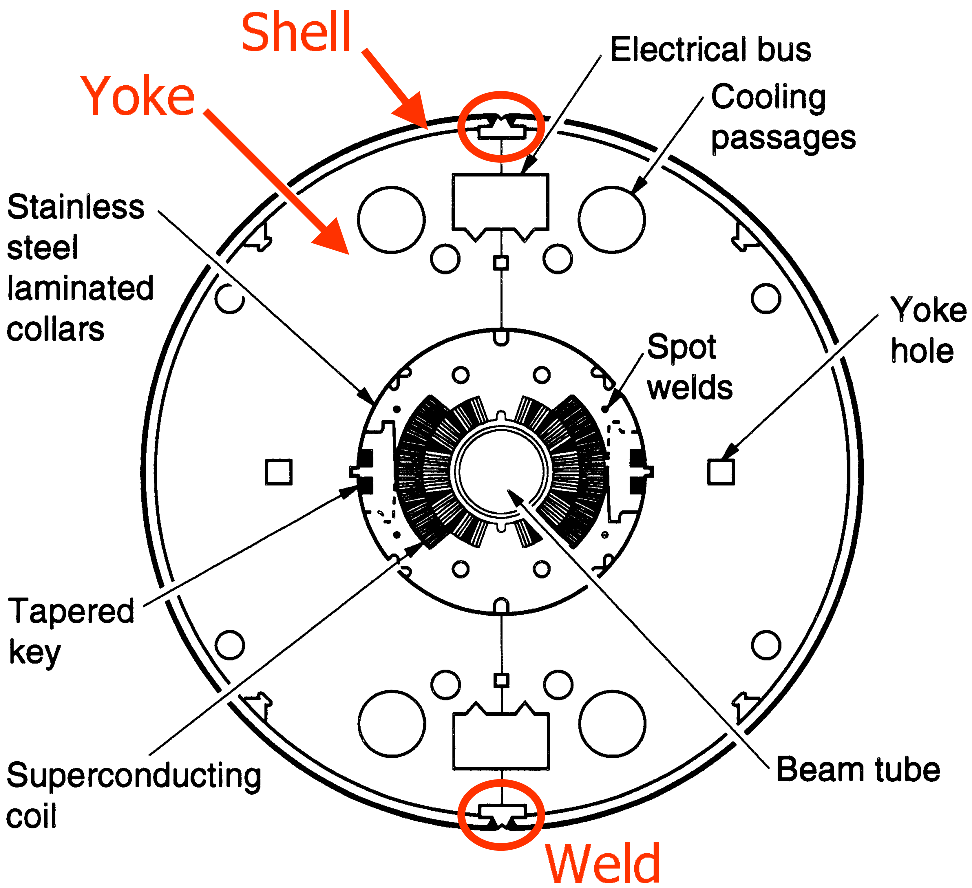
HERA Arc Quadrupole Magnet Design Developed at CEA/Saclay

Designs with Yoke Support

- In the magnetic design of high-field magnets, the field enhancement provided by the iron yoke is usually maximized by bringing it as close as possible to the coil.
- This reduces the space left for the collars, whose rigidity then becomes insufficient to contain the radial component of the Lorentz force.
- In such design, yoke and helium containment shell must also be used as part of the coil support structure.

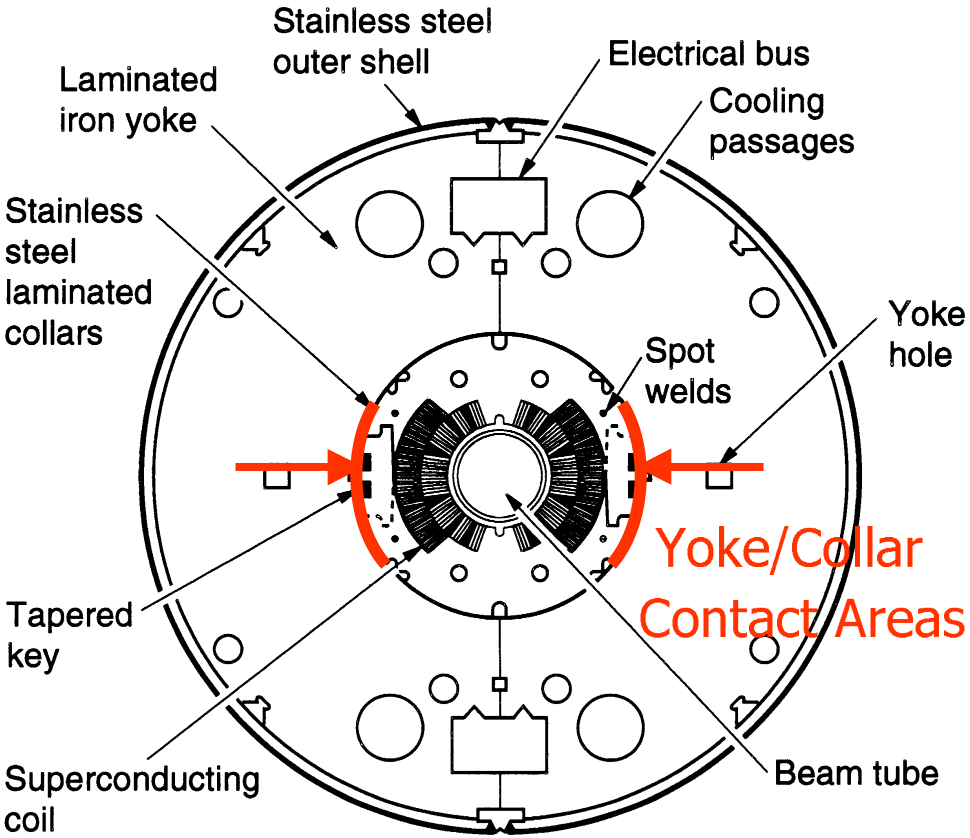
Example: SSC dipole magnet design.

Example: SSC Dipole Magnets (1/3)



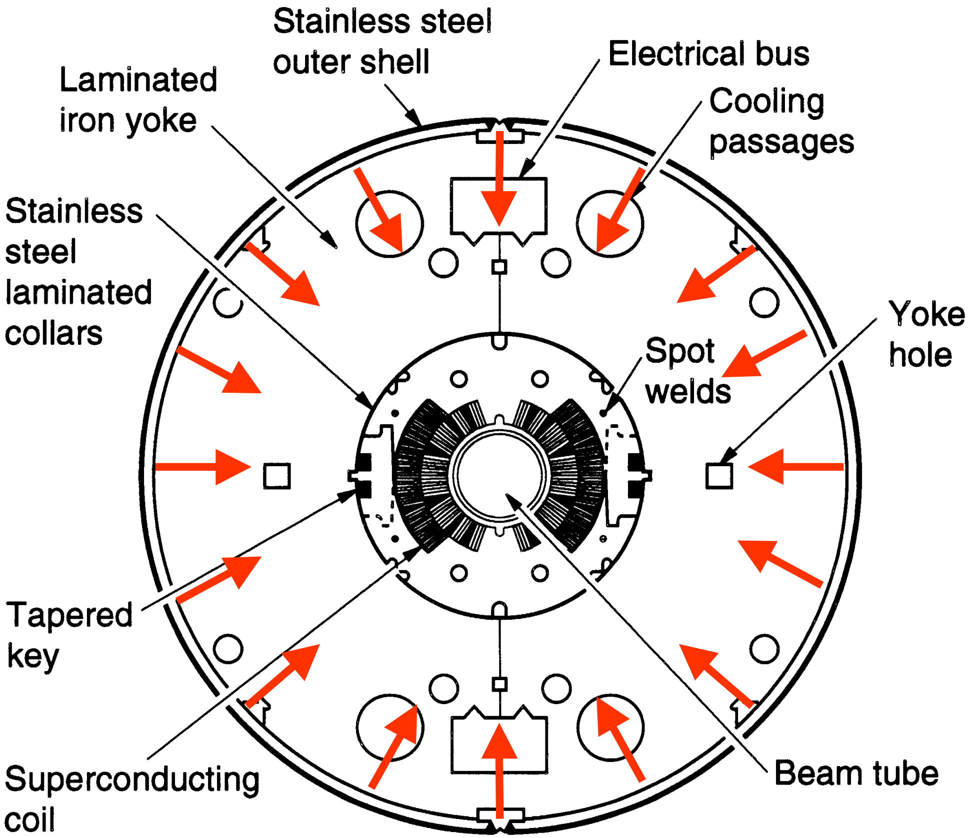
- In SSC Dipole Magnets, the yoke is split in two halves, which are mounted around the collared-coil assembly.
- The cold mass is completed by an outer shell, also split in two halves, which are welded around the yoked assembly.

Example: SSC Dipole Magnets (2/3)



- The structure is assembled so that the yoke halves apply a compressive load over selected areas of collared-coil assembly.

Example: SSC Dipole Magnets (3/3)



- The desired compressive load is obtained by welding the shell so as to apply a suitable radial pressure onto the yoke.

Contact Loss During Cooldown (1/3)

- The mechanical design of magnets with yoke support is complicated by the fact that the material used for the collars (stainless steel or aluminum) has a larger integrated thermal shrinkage coefficient than the low carbon steel used for the yoke.
- Hence, during cooldown, the collared-coil assembly has a tendency to shrink away from the yoke, which can result in a contact loss.

Contact Loss During Cooldown (2/3)

- This contact loss can be limited (and even eliminated) by introducing a thermal shrinkage allowance into the geometry of either the collars or the yoke.
- An estimate of the needed allowance, $\Delta R_{\text{c.d.}}$, is given by

$$\Delta R_{\text{c.d.}} \approx R_{\text{collar}} \left(\alpha_{\text{collar}} - \alpha_{\text{yoke}}\right)$$

where R_{collar} is the collar outer radius, and α_{collar} and α_{yoke} are the collar and yoke thermal shrinkage coefficients, integrated between room and liquid helium temperatures.

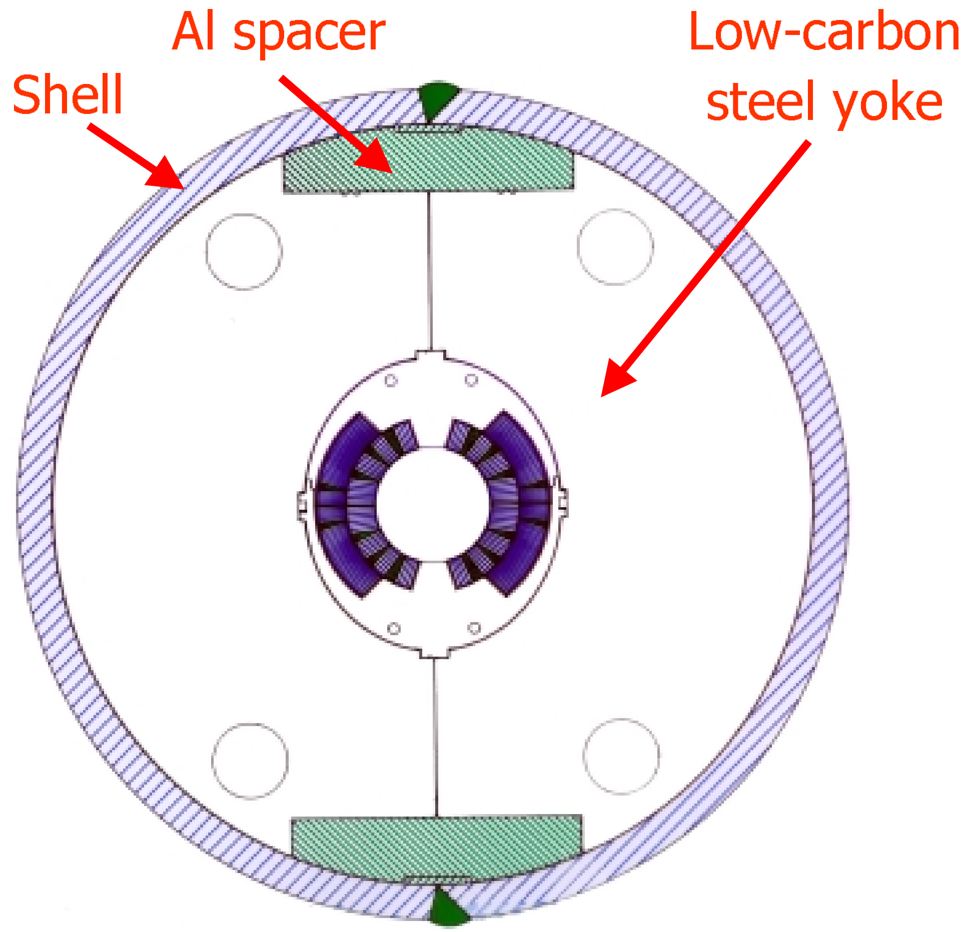
Collar Material (Bis)

- The above equation shows that to limit the amplitude of the shrinkage allowance, it is preferable to use for the collars a material whose integrated thermal shrinkage coefficient approaches that of low carbon steel.
- This suggests the use of austenitic stainless steel.
- However, and as already discussed in the previous section, it is also desirable to limit prestress loss during cooldown, which favors the use of aluminum alloy.

Radial Pressure From Shell Welding

- As we have seen, the compressive load applied by the yoke onto the collared-coil assembly arises from the radial pressure locked in the structure as a result of shell welding.
- This radial pressure must be large enough to ensure that, after cooldown and upon energization, the yoke remains in contact with the collared-coil assembly.
- However, it is also crucial to ensure that the applied radial pressure does not over-squeeze the collared-coil assembly at room-temperature.

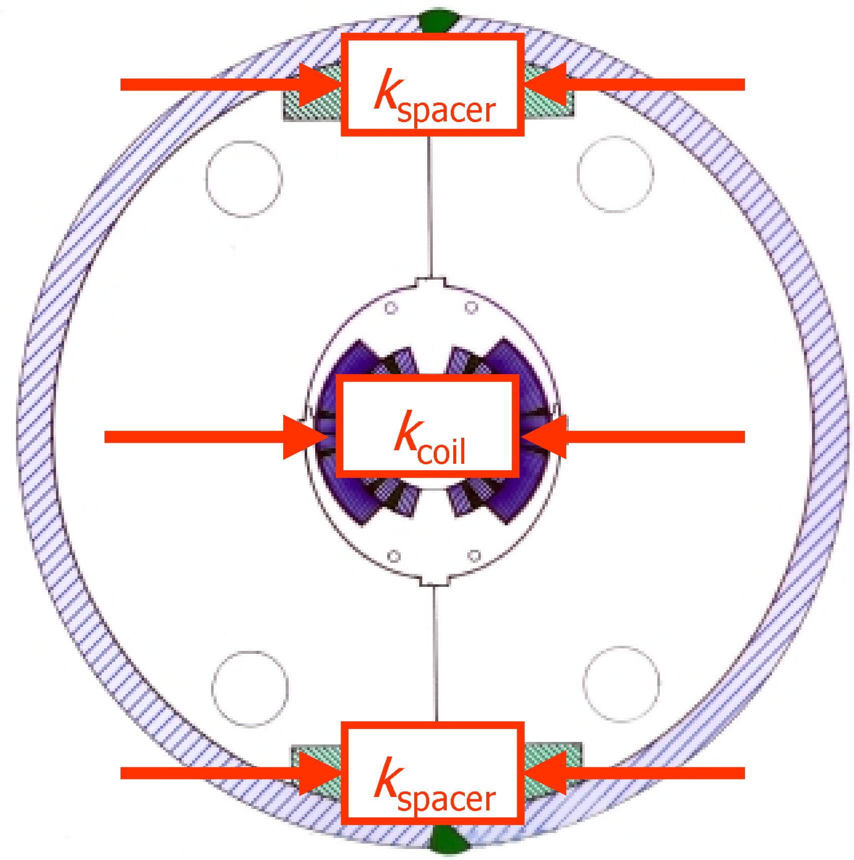
Aluminum Control Gap Spacers (1/4)



LBNL Dipole Magnet Model D19

- One way to prevent this over-squeeze is to implement aluminum spacers that control the mating of the two yoke halves.
- These spacers are designed to have a spring rate constant similar to that of the collared-coil assembly.

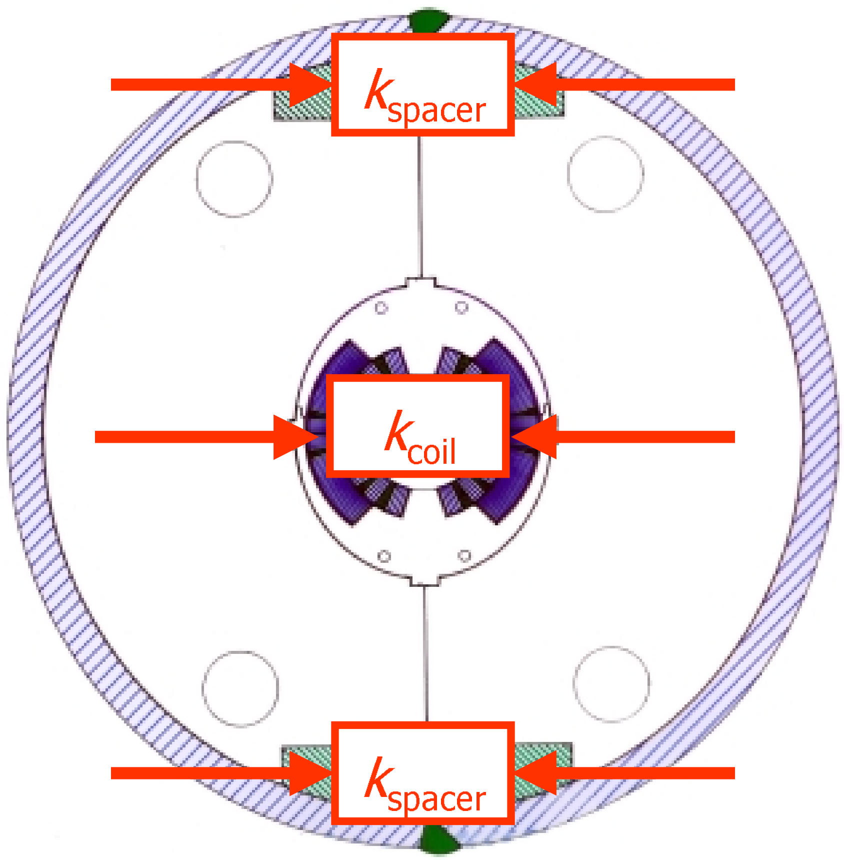
Aluminum Control Gap Spacers (2/4)



- Then, at room temperature, the welding of the shell results in a parallel loading of the three springs corresponding to the collared-coil assembly and the two spacers.

LBNL Dipole Magnet Model D19

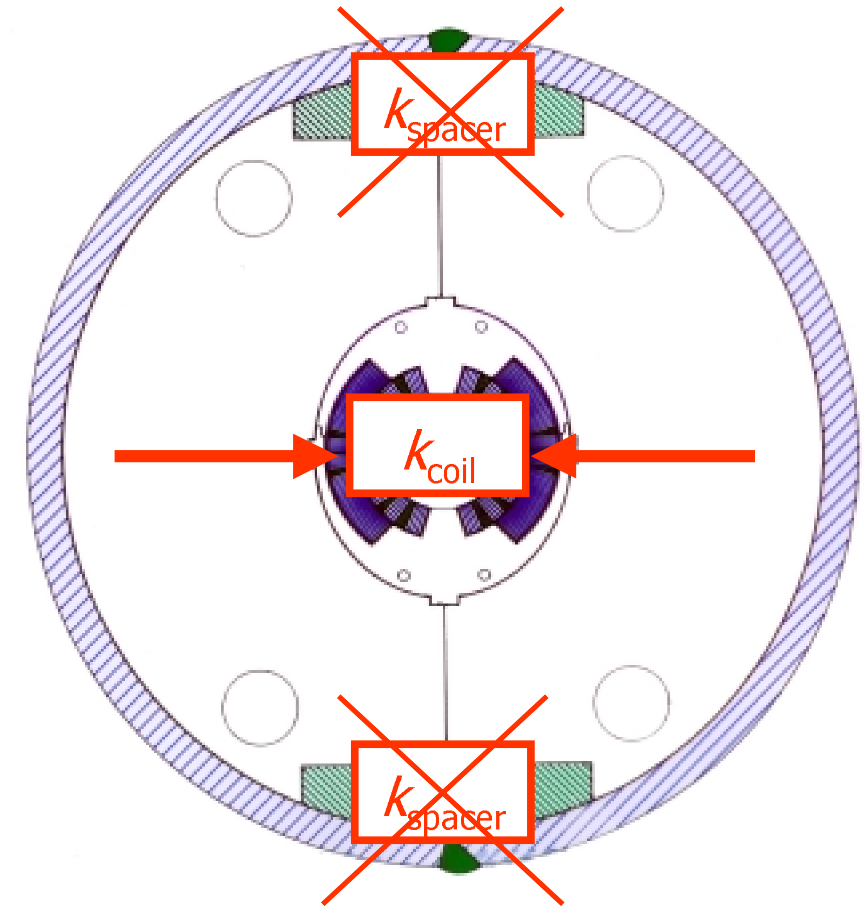
Aluminum Control Gap Spacers (3/5)



- Given the respective spring rates, the spacers prevent a full mating of the two yoke halves, thereby limiting the compressive load applied to the collared-coil assembly.

LBNL Dipole Magnet Model D19

Aluminum Control Gap Spacers (4/5)



LBNL Dipole Magnet Model D19

- During cooldown, the aluminum spacers shrink more than the low-carbon steel yoke and become loose.
- This enables a proper mating of the yoke halves and a suitable support of the collared-coil assembly.
- From then on, the spacers do not play any more role.

Aluminum Control Gap Spacers (5/5)

- So far, only four NbTi dipole magnets incorporating control-gap spacers have been built and tested (one 1-m-long, single-aperture model at LBNL and three 14-m-long, twin-aperture dipole magnet prototypes at CERN).
- The LBNL model reached 10 T at 1.8 K (after some training), while the CERN prototypes were less successful (for reasons that may have nothing to do with these spacers).
- More work is therefore needed to assess the usefulness and reliability of this feature.

Summary

- Given the complexity of mechanical designs seeking a yoke support, it is preferable to avoid having to deal with it.
- If it cannot be avoided, one should stress again the necessity of performing a thorough mechanical analysis of the structure under the various loading conditions encountered during assembly and operation.
- This analysis must be complemented by the manufacturing and testing of a number of fully-instrumented magnet models.

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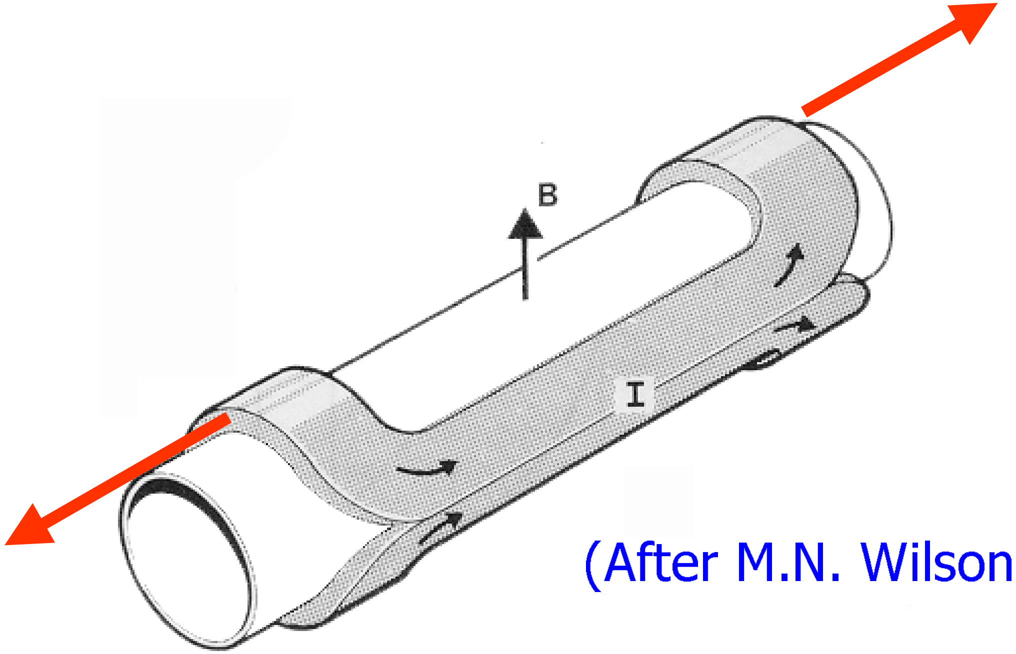
End Support (1/3)

- As we have seen, the axial component of the Lorentz force tends to stretch the coil outwardly.



(After M.N. Wilson)

End Support (2/3)

- In magnet designs where the yoke is not needed to support the collared-coil assembly, a clearance can be left between the two.
- Then, if the axial stresses resulting from the Lorentz force do not exceed the yield stress of the coil, it is possible to let the collared-coil assembly expand freely within the iron yoke.

Examples: HERA and LHC arc quadrupole magnet designs developed at CEA/Saclay.

End Support (3/3)

- However, in magnets where there is contact between collar and yoke, it is imperative to prevent stick/slip motions of the collar laminations against the yoke laminations.
- Then, a stiff support must be provided against the axial component of the Lorentz force.

Examples: the ends of SSC and LHC magnets are contained by thick end plates welded to the outer shell.

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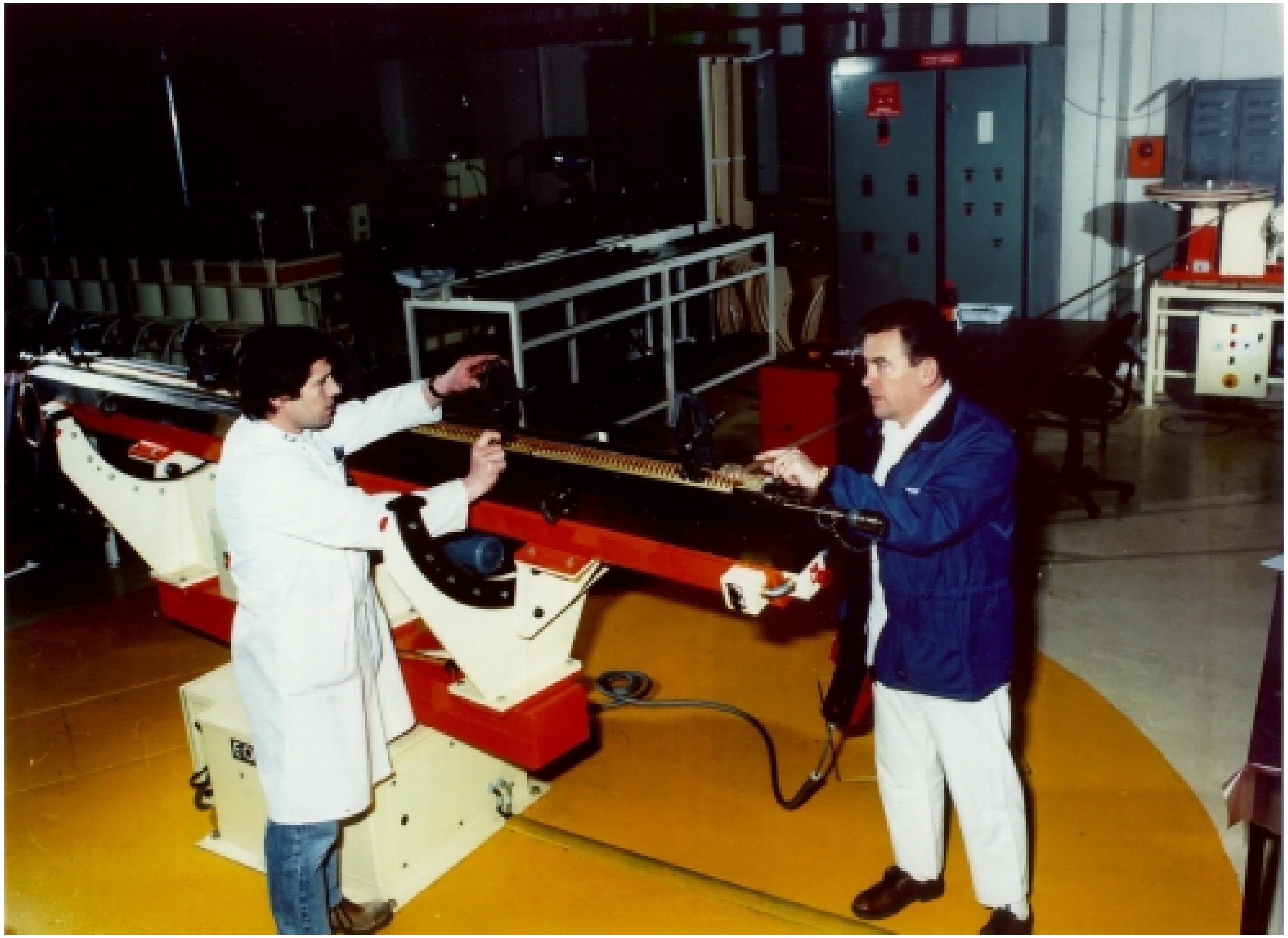
- **Manufacturing of NbTi Magnets**

Manufacturing Procedure

- The main steps of NbTi magnet manufacturing are
  - coil winding,
  - coil curing,
  - azimuthal coil size measurements,
  - coil assembly,
  - collaring,
  - yoking,
  - shelling.

Winding (1/2)

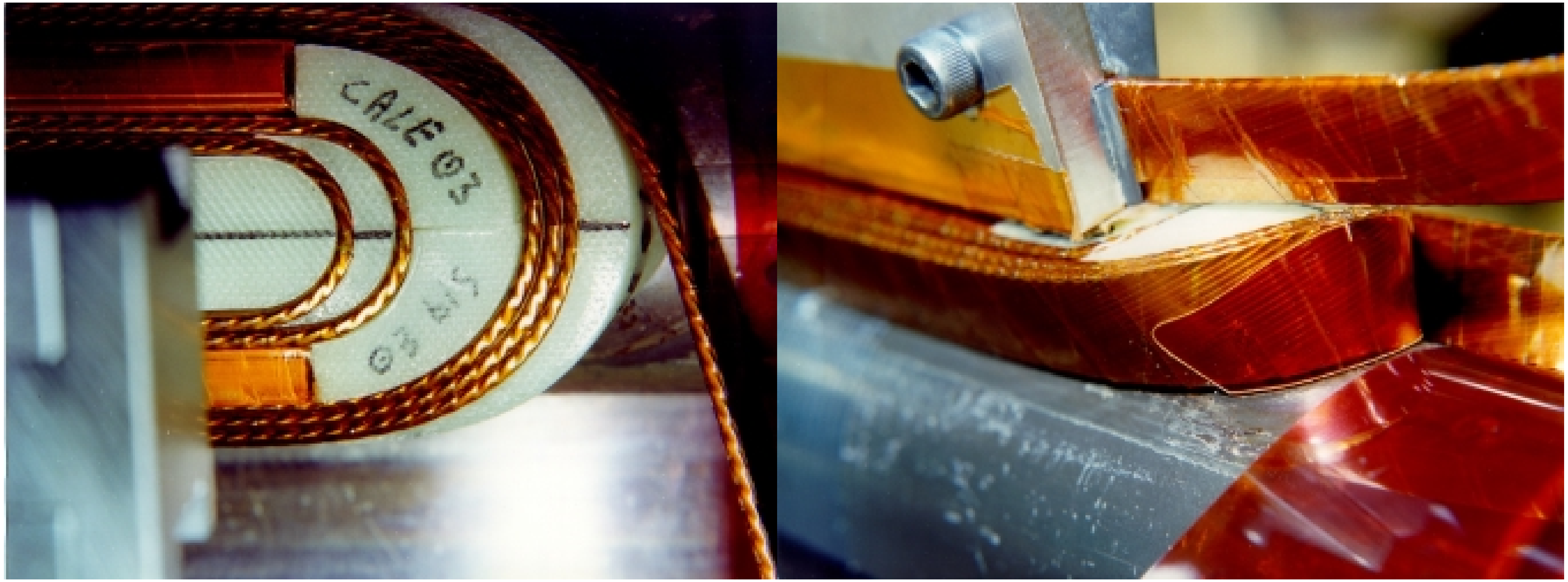


Rotating Winding Machine for 3-m-Long
LHC Arc Quadrupole Magnet Coils at CEA/Saclay

Winding (2/3)

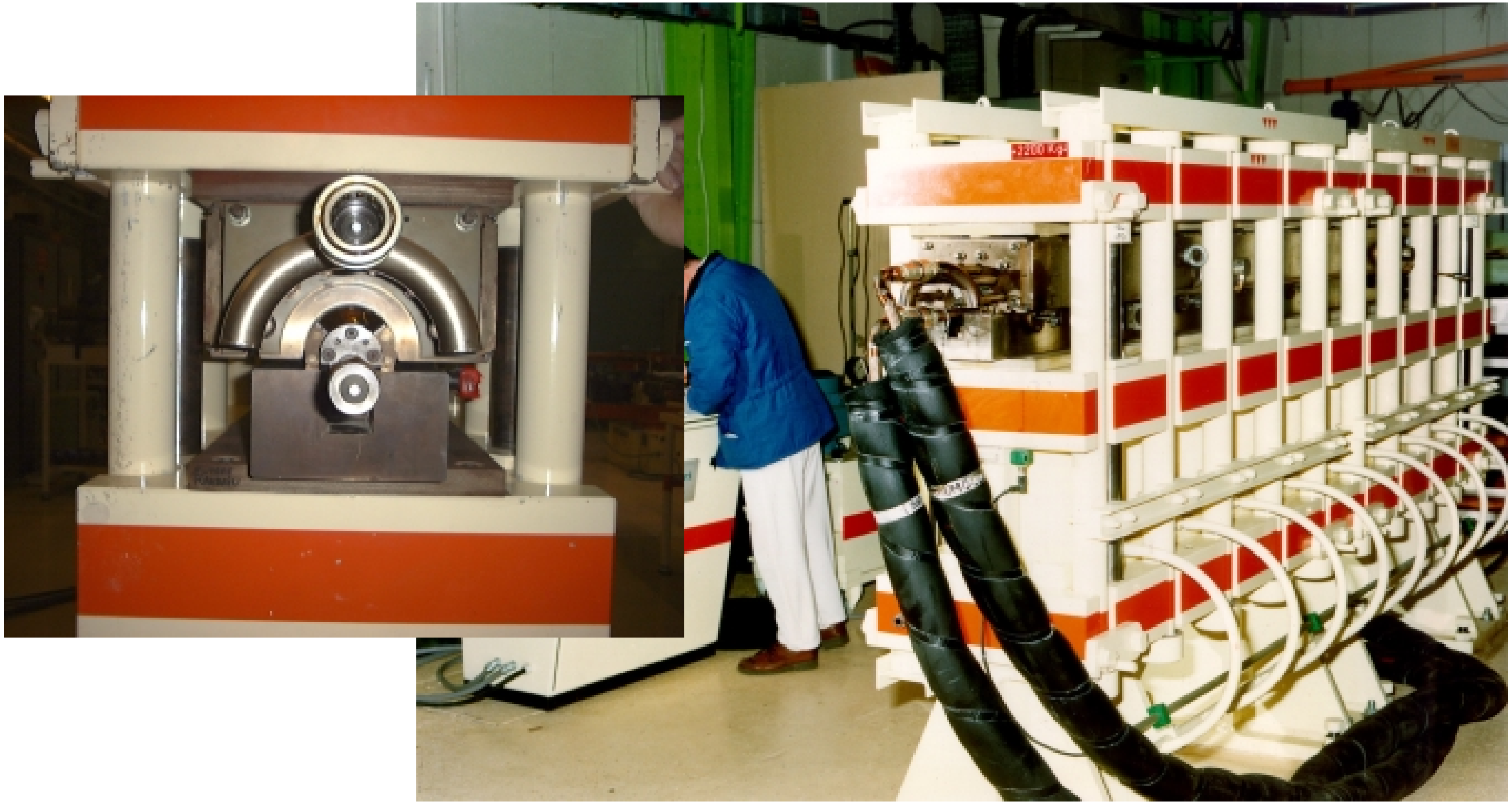
Shuttle-Type Winding Machine
For 15-m-Long SSC Dipole Magnet Coils at BNL
(Now Dismantled)

Winding (3/3)



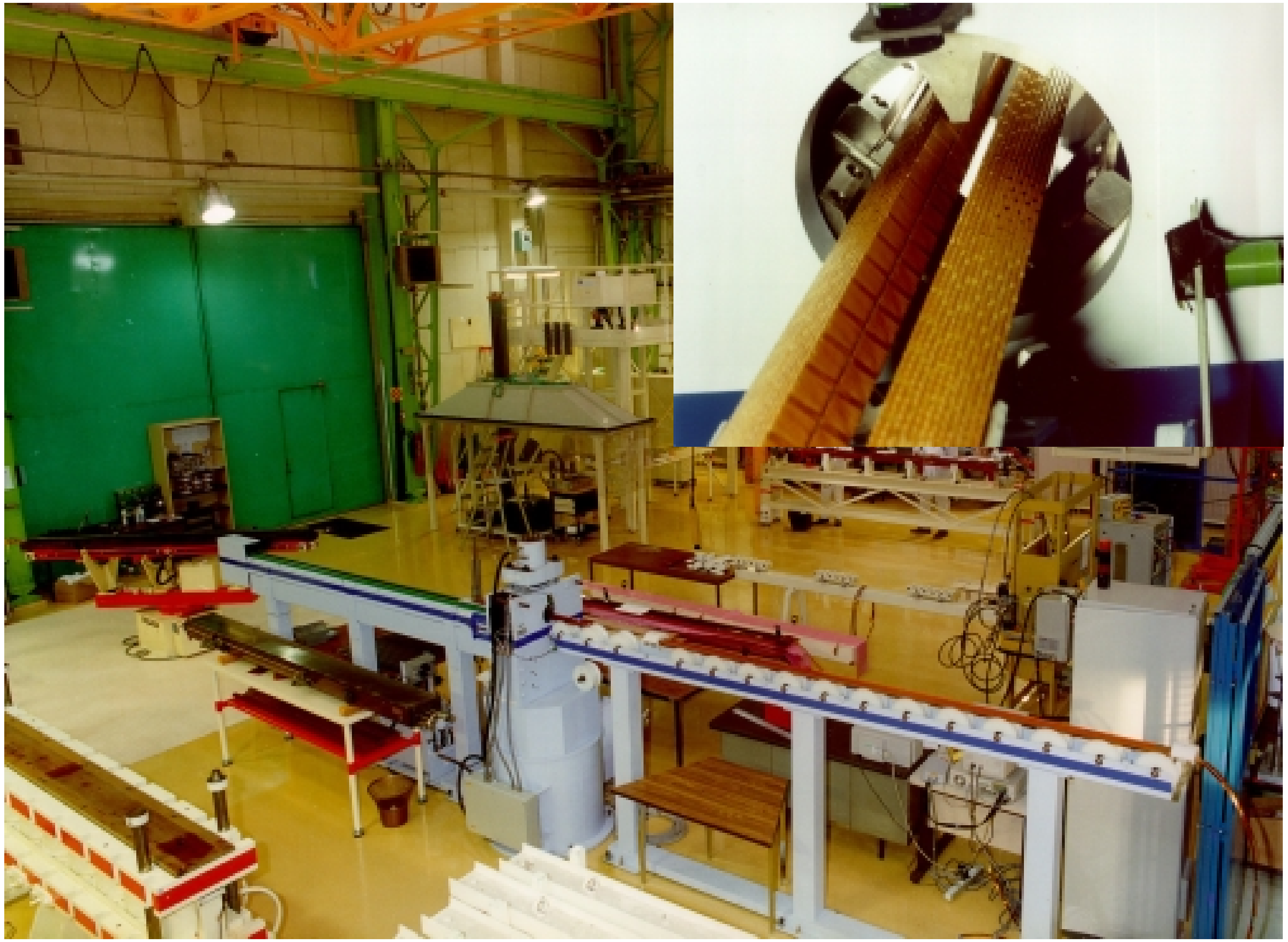
Winding of LHC Arc Quadrupole Magnet Coil Ends
at CEA/Saclay

Curing



Curing Press for 3-m-Long, LHC Arc
Quadrupole Magnet Coils at CEA/Saclay

Coil Size Measurements



Automatic Azimuthal Coil Size Measuring Machine for 3-m-Long, LHC Arc Quadrupole Magnet Coils at CEA/Saclay

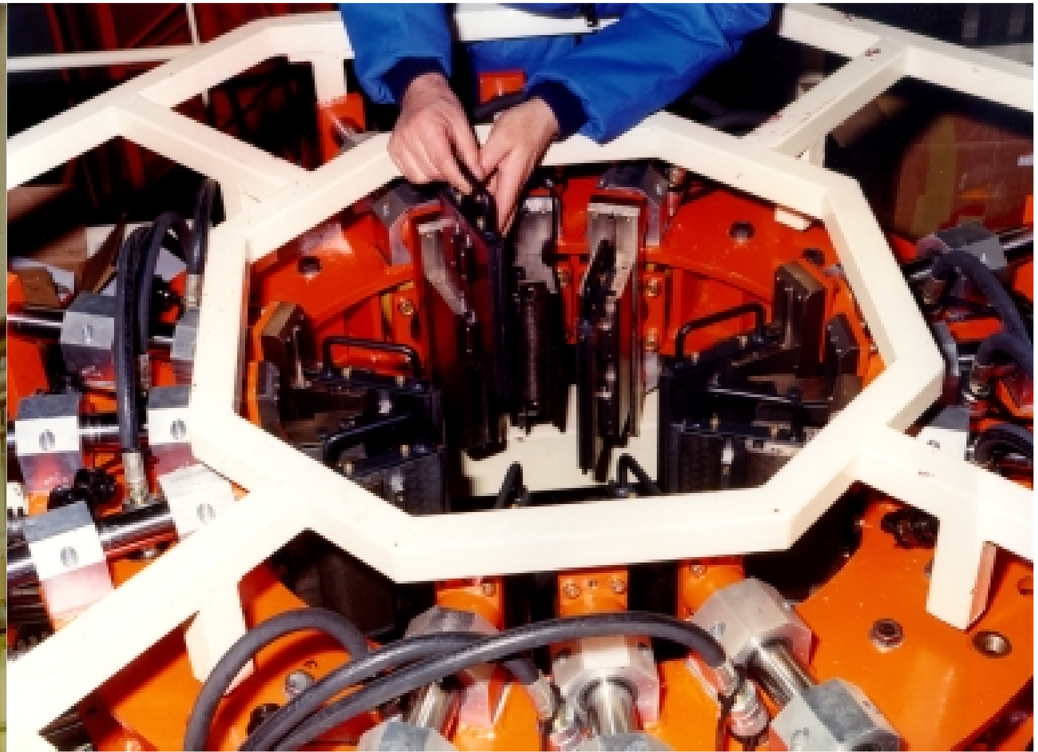
Coil Assembly

Assembly of 15-m-long LHC Arc
Dipole Magnet Coils at Alstom/MSA

Collaring (1/2)

Collaring Press for 15-m-long, twin-aperture LHC Arc Dipole Magnets at Alstom/MSA

Collaring (2/2)



Vertical Collaring Press
for 3-m-long LHC Arc Quadrupole
Magnets at CEA/Saclay

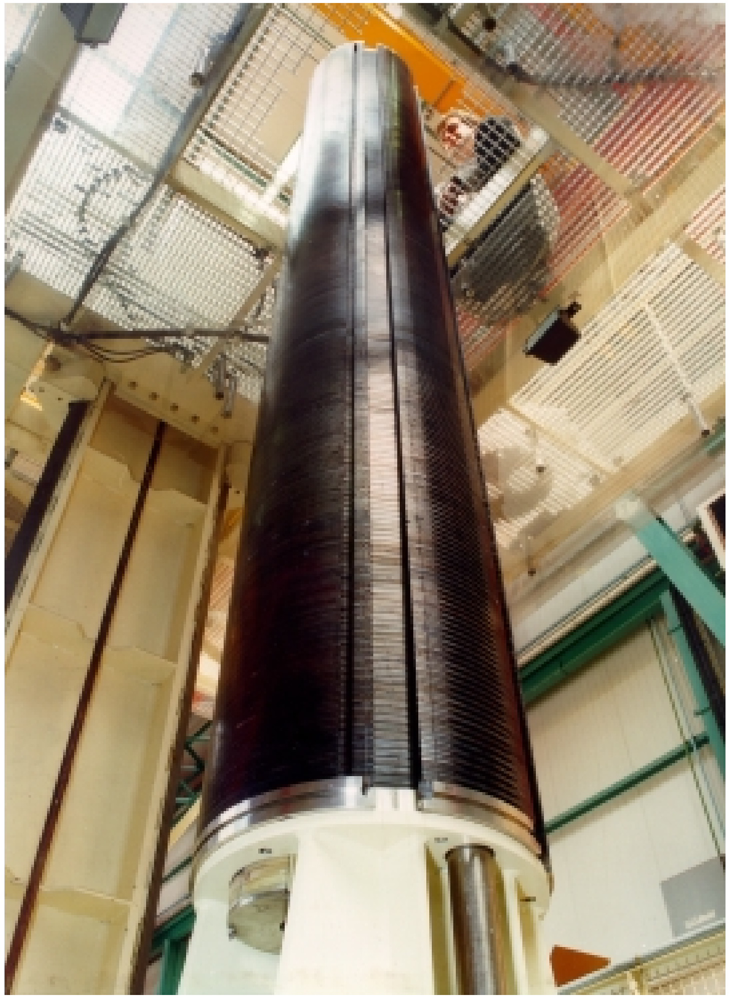
Yoking (1/3)

Handling of Collared-Coil Assembly
In Preparation for Yoking: SSC at BNL (left)
and LHC at CEA/Saclay (right)

Yoking (2/3)

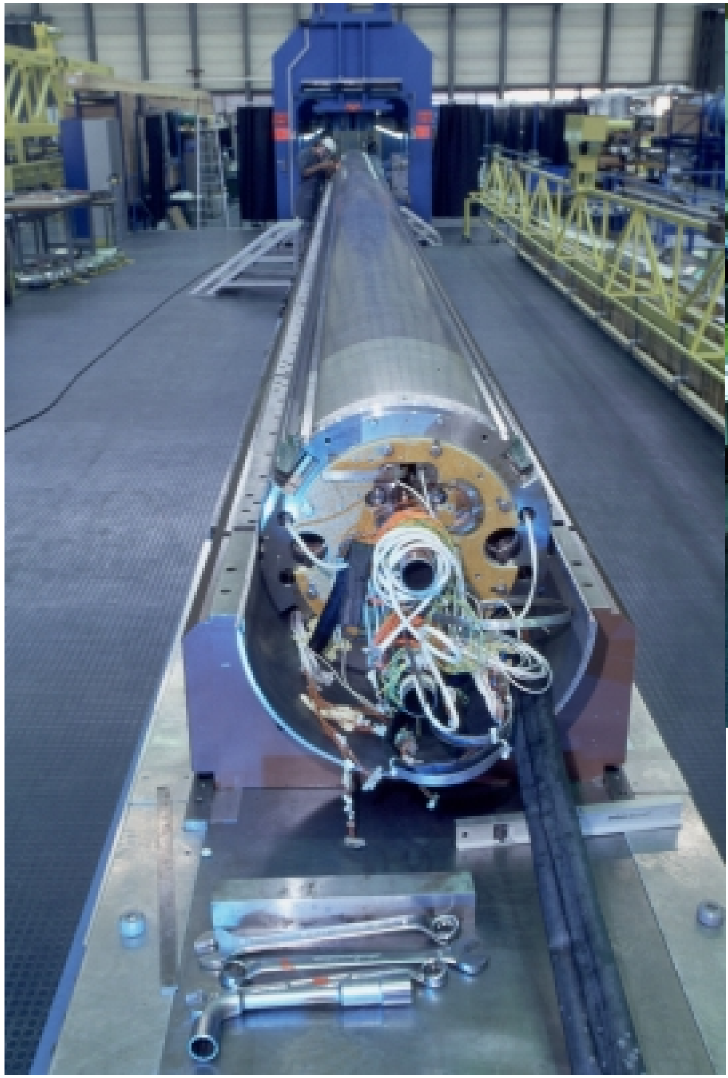
Yoking of 15-m-Long, Single-Aperture SSC Arc Dipole Magnet at BNL

Yoking (3/3)



Vertical Yoking of 3-m-Long, Twin-Aperture
LHC Arc Quadrupole Magnet at CEA/Saclay

Shelling (1/5)

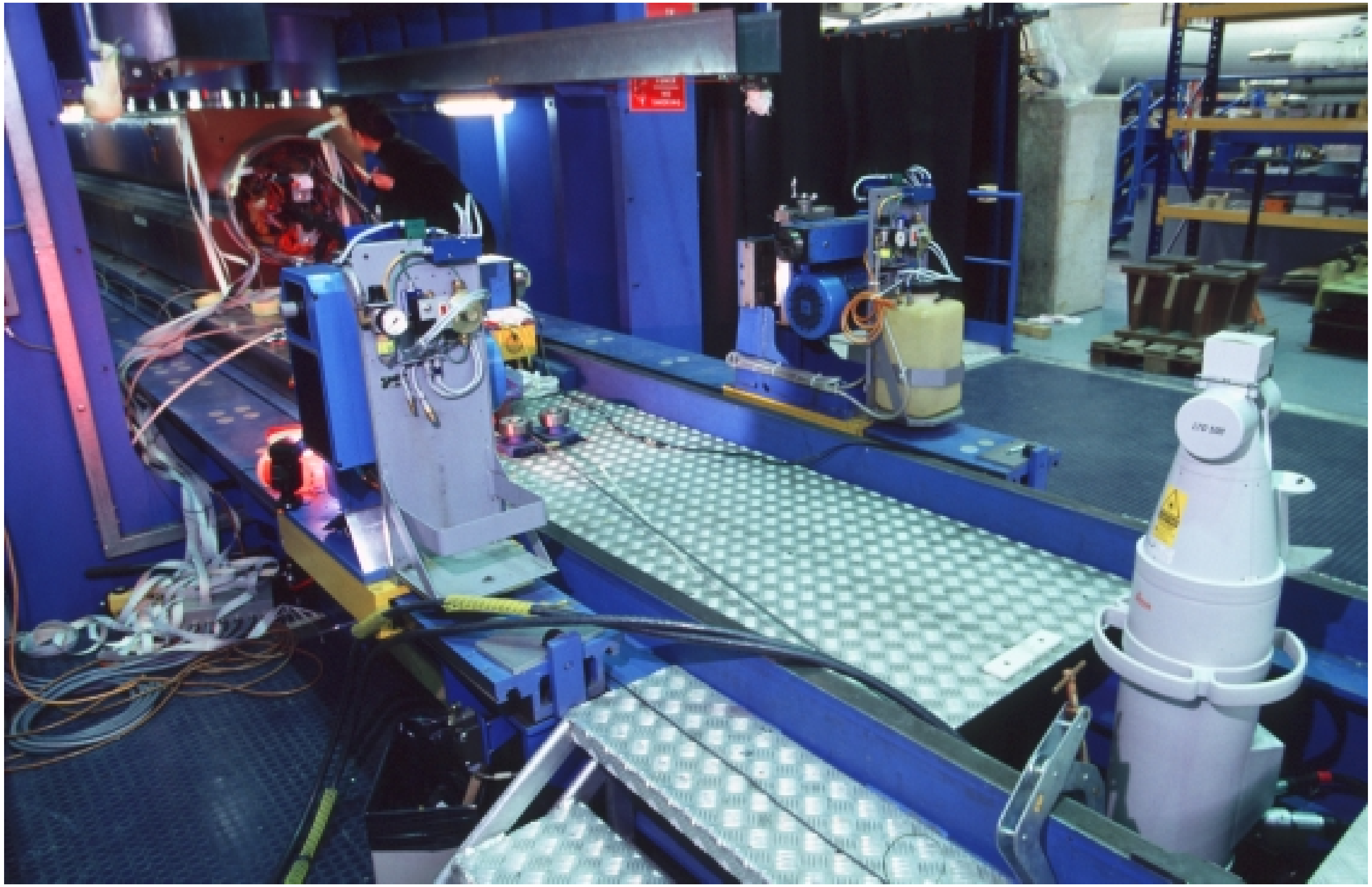


Shell-Welding Preparation
For 15-m-Long, Twin-Aperture
LHC Arc Dipole Magnet at CERN

Shelling (2/5)

Shell-Welding Press for 15-m-long, Twin-Aperture LHC Arc Dipole Magnets at Alstom/MSA

Shelling (3/5)

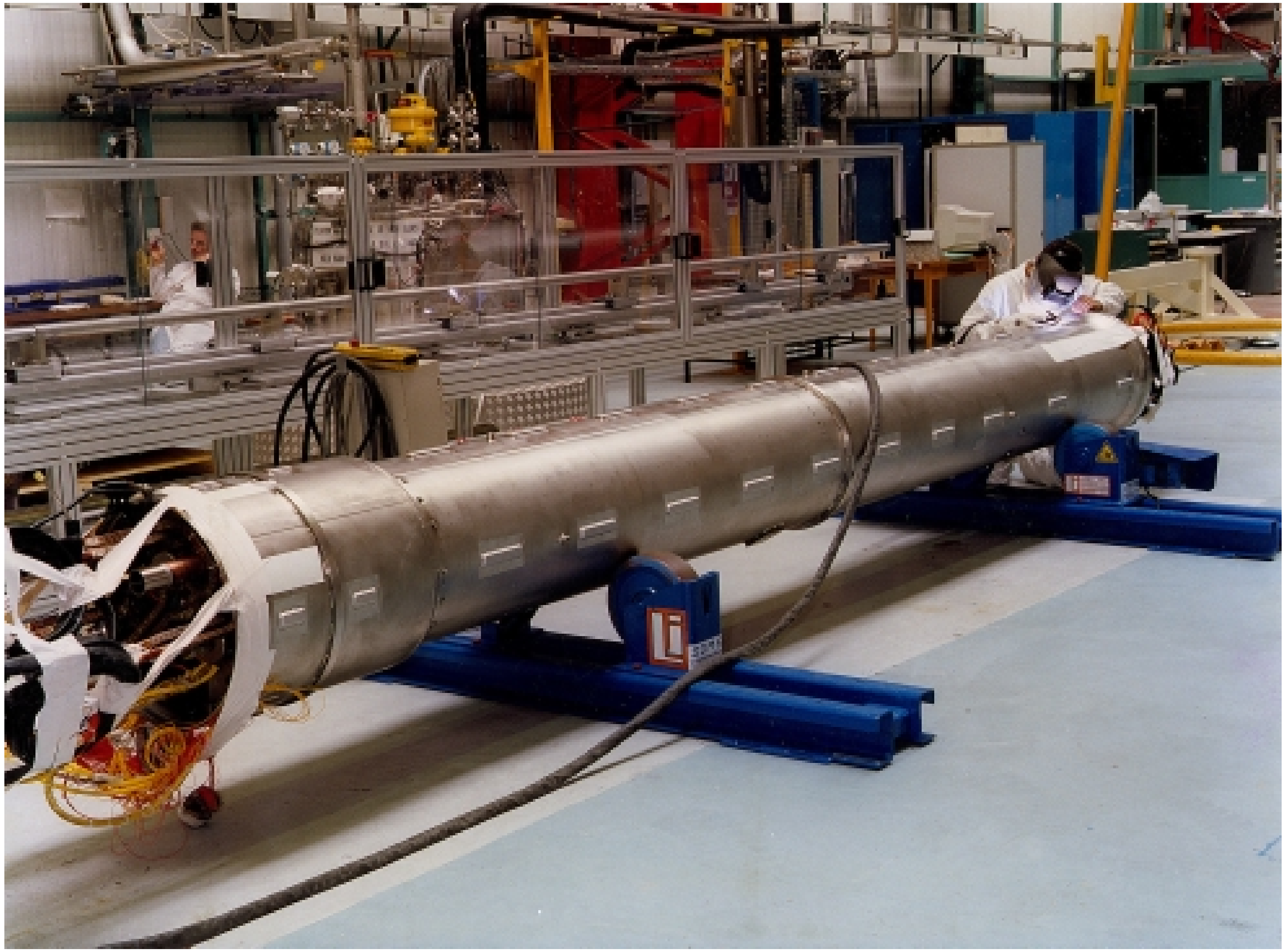


Shell-Welding Equipment For 15-m-Long, Twin-Aperture
LHC Arc Dipole Magnets at CERN

Shelling (4/5)

Insertion of Outer Cylinder
on 3-m-Long, Twin-Aperture
LHC Arc Quadrupole Magnet
at CEA/Saclay

Shelling (5/5)



Welding of End Domes on 3-m-Long, Twin-Aperture LHC Arc Quadrupole Magnet at CEA/Saclay